S P E C I F I C A T I O N

1 X N OR N X 1 OPTICAL SWITCH HAVING A PLURALITY OF MOVABLE LIGHT GUIDING MICROSTRUCTURES

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This patent application is a continuation-in-part and claims priority of the following related patent applications: (1) provisional U.S. Patent Application Serial No. 60/233,672 by Ying Wen Hsu, filed on September 19, 2000 and titled "Method For Switching Optical Signals Using Microstructures;" (2) provisional U.S. Patent Application Serial No. 60/241,762 by Ying Wen Hsu, filed on October 20, 2000, titled "Method for switching optical signals using microstructures;" (3) U.S. Patent Application Serial No. 09/837,829 (docket 263/176) by Ying Wen Hsu, filed on April 17, 2001 and titled "Optical Switching Element Having Movable Optically Transmissive Microstructure;" (4) U.S. Patent Application Serial No. 09/837,817 (docket 263/214) by Ying Wen Hsu, filed on April 17, 2001 and titled "Optical Switching System That Uses Movable Microstructures To Switch Optical Signals In Three Dimensions," all patent applications of which are expressly incorporated herein by reference. This patent application is also related to U.S. Patent Application Serial No. 09/_______ (docket 266/089) by Ying Wen Hsu and Arthur Telkamp, filed concurrently with the present patent application and titled "Low Loss Optical Switching System," which is incorporated herein by reference.

BACKGROUND OF THE INVENTION

Field of the Invention

[0002] The field of the invention is optical switches for switching light and in particular, multiple-stage optical switches having N outputs.

Background

[0003] Optical switches in various forms are used today in the telecommunication routing applications. At the junctions of these networks, the switches first convert optical signals into electrical signals and then direct (switch) the light into the desired channel. After switching, the electrical signal is converted back into optical signals before it is sent to the next destination. Such repetitive conversions between optical and electrical form increase the cost and power consumption in routing equipment and greatly limit the amount of signals the network is capable of delivering.

[0004] Optical switches exist in various configurations. For example, a M x N optical switch refers to a switch having M inputs and N outputs. There is a need for a small optical switch that is capable of switching light into multiple ports, while maintaining low optical loss and having low power dissipation. There is also a need for a cost effective method of fabricating such an optical switch.

SUMMARY OF THE INVENTION

[0005] Generally, the improved 1 x N or N x 1 optical switch uses waveguides or other light guiding structures disposed on a plurality of movable platforms to switch an optical signal from one input port to any of N output ports, or switching any of N input optical signals to one fixed output port.

[0006] Other systems, methods, features and advantages of the invention will be or will become apparent to one with skill in the art upon examination of the following figures and detailed description. It is intended that all such additional systems, methods, features and advantages be included within this description, be within the scope of the invention, and be protected by the accompanying claims.

BRIEF DESCRIPTION OF THE DRAWINGS

[0007] The components in the figures are not necessarily to scale, emphasis instead being placed upon illustrating the principles of the invention. Moreover, in the figures, like reference numerals designate corresponding parts throughout the different views. However, like parts do not always have like reference numerals.

[0008] FIG. 1 is an illustration of an example embodiment of a 1 x N optical switch where the motion of the moving platforms is linear.

[0009] FIG. 2 is an illustration of another example embodiment of a 1 x N optical switch where the motion of the moving platforms is rotational.

[0010] FIGS. 3-9 are cross-sectional illustrations of steps in an example process of fabricating an optical component.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0011] The improved 1 x N optical switch is a small element capable of switching an optical signal from one input port to any of N output ports, or by reversing the direction, switching any of N input optical signals to one output port. By combining these elements into an array configuration, a large number of ports can be interconnected. These switch arrays are referred to as Optical Cross Connects and are expected to become widely used in future optical telecommunications.

[0012] The improved 1 x N optical switch is fabricated by arranging an assembly of movable structures, comprising of a main body and at least two independent moving platforms (also referred to as "microstructures"). Optical waveguides are created on these platforms and the main body. By moving these platforms relative to each other, waveguides on one platform are either connected or disconnected from waveguides on the other platform. By controlling the relative motions of the platforms and the geometrical arrangement of the waveguides, an optical signal from one input port can be connected to any one of N output ports. The improved 1 x N optical switch is not limited to using waveguides since other light guiding structures or free-space optical transmissions techniques, such as lenses or mirrors, can be employed in place of or in addition to waveguides. In other words, the term "light guiding structure" as used in this patent application includes waveguides, lenses and mirrors. The movable platforms are

fabricated by employing Micro-Electrical-Mechanical System (MEMS) technology, which is well known in the art.

[0013] The improved 1 x N optical switch is capable of connecting one optical input port to any of N output ports, or in reverse, any of N input signals to one output port. FIG. 1 illustrates an example of a preferred embodiment of the improved 1 x N optical switch 10. In particular, FIG. 1 illustrates an example embodiment of a 1 x 9 optical switch, meaning that the optical signal from one input port A can be switched to any one of nine output ports B-J. In the preferred embodiment of the improved 1 x N optical switch, movable microstructures (also called platforms) and waveguides are used to switch optical signals.

[0014] The 1 x N optical switch 10 has two types of platforms. The first type is the movable platform 22, 23. The second type is the stationary platform 21, 24. The two movable platforms 22, 23 are suspended a distance from the substrate 41 such that each platform is free to move relative to each other. Optionally, a cavity may be formed in the substrate 41 in order to suspend the movable platforms 22, 23 away from the substrate 41. On the top of these platforms 22, 23 are waveguides 28, 30, or other light guiding structures. Preferably, the waveguides 28, 30, 25 and 26 are deposited with a semiconductor process on top of the stationary platforms 21, 24 and the movable platforms 22, 23 using waveguide manufacturing procedures described below and in the art of semiconductor processing. By using the proper geometrical arrangement, at least one waveguide optical path is made between the two movable platforms 22, 23. This concept is similar to the Verniers calipers commonly used in the machine industry for

determining the position of an object. In a Verniers caliper, the distance moved or measured is determined by the alignment between two scales in slightly different graduations. In the preferred embodiment of the improved 1 x N optical switch, the scales are replaced by optical waveguides. By controlling the position of the movable platforms 22, 23 relative to each other, which platforms carry the waveguides 28, 30, one waveguide can always be made to be connected to the optical path, while the rest are disconnected from the optical path. FIG. 1 illustrates the optical path extending from input port A to output port F. In other words, the only output port connected to the optical path to the input port A is output port F.

Linear Optical Switches

[0015] The headings used in this specification are intended to guide the reader and do not limit the scope of the invention in any way. Thus, any disclosures and teachings from one section are applicable to another section, and vice versa.

[0016] Preferably, the 1 x N optical switch 10 allows the movable platforms 22, 23 to have a single degree-of-freedom motion. Both movable platforms 22, 23 can occupy one of three positions: a center position, a +Y position, or a -Y position. In FIG. 1, the movable platforms 22, 23 move linearly and are referred to as linear platforms. In FIG. 1's illustration of a 1 x 9 optical switch, the input optical signal can have a path to nine different output ports B-J. With both linear platforms 22, 23 at rest in their center position, which preferably is their position when no power is applied to the optical switch, a default optical signal path is connected straight through from input port A to

output port F. When a linear platform 22, 23 moves either +Y or -Y from its center position, the input optical signal path can then be routed to a different output port. In this example embodiment, all signal routings are done with waveguides on stationary platforms 21, 24 and movable platforms 22, 23. Input waveguide 25 and output waveguides 26 are placed over stationary platforms 21, 24 that are mounted or fixed to the substrate 41.

[0017] The optical switch 10 in FIG. 1 operates as follows: an optical signal is introduced into the stationary waveguide 25 at input port A. The first movable platform 22 is moved into one of its three positions (up, +Y or -Y). The optical signal then traverses across a small air gap 27 and enters into one of three waveguide paths 28 on the first movable platform 22. From the first movable platform 22, the optical signal (i) travels across a second small air gap 29, (ii) enters into a second movable platform 23, (iii) propagates along one of three waveguide paths 30, depending upon the position (+Y, center or -Y) of the second movable platform 23 relative to the first movable platform 22, (iv) exits by traversing across a third small air gap 31 into one of the stationary waveguides 26, and (v) exits to one of nine output ports B – J.

[0018] In the example embodiment, the movable platforms 22, 23 are suspended over a backside-etched opening in the substrate 41 and are supported by springs 33, 34, preferably etched from the same material as the platforms 22, 23. The springs 33, 34 are connected to the substrate 41 by support blocks 35 and stationary platforms 21, 24. The movable platforms 22, 23 are connected to a set of electrodes 36, which preferably have fingers shaped like combs and are interdigitally matched to an opposing set of electrodes

37 fixed to the substrate 41. When an electrical voltage is applied across the two electrodes 36, 37, the voltage differential generates an electrostatic attraction force, causing the platform 22, 23 to move. The movable platform shown in FIG. 1 is a linear platform design and hence, the platform moves in a linear direction. The springs 33, 34 deflect to allow the platform 22, 23 to move to the desired location. The use of electrostatic actuators to move microstructures is well known to those skilled in the art of MEMS design.

[0019] Further, the 1 x N optical switch 10 preferably attempts to maximize the radii of the curvatures in the waveguides and does not have waveguide path crossovers. The improved 1 x N optical switch 10 thus changes the optical path of the waveguide gradually, which reduces optical loss. Furthermore, the movable platforms 22, 23 move along in one direction only, i.e. a single degree of freedom, thus simplifying the design of the controller of the optical switch. A single degree of freedom motion also greatly simplifies the design of the supports and actuators for the movable platforms.

[0020] The number of output ports in the improved 1 x N optical switch can be increased by increasing the number of platforms, or by increasing the number of movable positions that each movable platform 22, 23 has. For example, an optical switch system that has two movable platforms 22, 23, each platform having three positions, can switch a single input to any of 9 outputs. If another 3-position movable platform is added, the number of possible outputs increases to 27. Similarly, in a system having only two movable platforms, if the number of movable positions of each movable platform is increased from three to five, the number of outputs can be increased to 25. Increasing the

number of movable platforms adds complexity to the mechanical design, but increasing the number of positions per movable platform adds complexity to the electronics, which in turn necessitates complex analog and closed-loop control circuits or software.

[0021] With the improved 1 x N optical switch, the number of output ports N can be determined by the following relationship:

$N = L^p$, where p is the number of movable platforms and L is number of positions that each movable platform has, assuming that all movable platforms have the same number of possible positions. If the movable platforms have a different number of positions, a different appropriate formula can be determined.

[0022] To enable the waveguides to efficiently conduct light across air gaps, the movable waveguides 22, 23, must be aligned accurately with the fixed waveguides 21, 24. This can be accomplished in two ways. The first is to use a mechanical stop 18. The second is to rely on electronic position control. Mechanical stops can be integrated into the optical switch design. Since each platform 22, 23 moves between two maximum positions, one stop is required for each of the optimum +Y and optimum -Y direction. The achievable alignment accuracy is dependent on the accuracy of the etching process.

[0023] FIG. 1 illustrates using an optional set of electrodes 38, 39 for position sensing. The sensing electrodes 38, 39, as with the actuator electrodes 36, 37, are arranged preferably using interdigitated comb-like structures. The capacitance across the electrodes 38, 39 changes as the platforms 22, 23 move, which can be measured using appropriate detection circuits. The platforms 22, 23 can be positioned accurately based

on feedback information derived from the measured capacitance signal. To achieve high reliability, the signals from a sensing circuit can also be fed into a closed-loop control circuit such that the movable platform 22, 23 can be driven into the desired position. The electrodes 39 are routed to the edge of the substrate 41 for connection to wire bond pads 42. The electronic designs and method of sensing the position of an object by a measured change in the capacitance are well known to those skilled in design of MEMS structures.

[0024] A preferred method of manufacture of the improved 1 x N optical switch uses silicon on insulator (SOI) wafers. SOI are wafers covered with a thin silicon oxide (SiO_2) layer acting as an insulator, and a thin silicon layer bonded on top that serves as a device layer. The waveguides are formed on top of this device layer by depositing a thin layer of oxide using Plasma Enhanced Chemical Vapor Deposition (PECVD). A layer of silicon oxynitride (SiOxNy) is deposited and patterned by photolithographic processing. Finally the oxynitride is covered with another oxide layer which acts as a cladding. The device layer supporting the waveguides is then shaped by using any well known etching technique. In the example embodiment, the completed MEMS structures and movable platforms are suspended over an etched bottom cavity, supported by springs 33, 34 etched out of the same material as the movable platforms. The movable platforms 22, 23 are connected integrally to a set of comb shaped electrodes 36-39 which are used for electrostatic driving and capacitance position sensing.

[0025] The term "integral" as used in this patent application and claims refers to two structures that are coupled together by a semiconductor process. For example, if X is attached to Y by screws or bolts, X is not "integral" with Y. Further, the term "integral"

does not require the two structures to be formed out of monolithic materials; two structures can be deemed integral to each other if the structures are formed out of composite or multiple materials, as well as if the structures are formed out of monolithic materials. For example, X can be integral with Y even if X is a platform coupled to a device layer which has been formed on a substrate by a semiconductor process. Lastly, X can be integral with Y even if X is silicon with a doped material and Y is silicon doped differently as long as the silicon are coupled together by a semiconductor process.

[0026] Variations of the manufacturing process from those described herein are also permissible. For example, instead of using PECVD oxides, thermally grown oxides can be used; or instead of using oxynitride, one can use silica doped with germanium or other dopants. The final choice of the process and material depends on the system design and the designer's familiarity with certain waveguide and MEMS processes.

[0027] In designing optical switches, one of the key factors is Insertion Loss, a parameter that is a measure of the amount of light lost as a result of the optical signal traversing through the optical switch. Insertion loss is due to a number of contributors such as those related to fiber-to-waveguide coupling, waveguide transmission, waveguide crossovers, waveguide bends and air gaps. With respect to fiber-to-waveguide coupling, losses may be due to reflection of light at interfaces and mode mismatches. With respect to waveguide transmission, losses may be due to bulk absorption (e.g., loss due to the absorption of light by the waveguide material), scattering due to core sidewall roughness and coupling losses to the substrate or neighboring waveguides. With respect to waveguide crossovers, there may be diffraction losses. With respect to waveguide bends,

bend losses (e.g., losses due to light traversing a curved path in the waveguide) may occur. With respect to air gaps, losses may be due to reflection of light at waveguide-air interfaces and diffraction of light as the light propagates unguided through free space. Thus, the design should minimize individual losses and balance the losses between different mechanisms in order to yield the lowest total insertion loss. In addition to the insertion loss and small element size, other requirements such as power, switching time and polarization effects are also important to consider.

Rotational Optical Switches

[0028] FIG. 2 illustrates another example embodiment of a 1 x N optical switch 100 where the motion of the moving platforms 136, 138 is rotational rather than linear. An input light signal 130 enters port M through a waveguide 134 and is routed to any one of the 9 output ports 132 (e.g., N to V) by virtue of movably positioning platforms 136 and 138. The terms "movable" or "movably" as used anywhere in this disclosure are intended to include both rotational and linear movements, as well as other possible movements. If movable platform 136 is rotated clockwise, the stationary waveguide 134 can be made to align with waveguide 140 on the movable platform 136. When the movable platform 136 is in this rotated position relative to the second stationary platform 138, the waveguide 140 is in alignment with waveguide 142, and subsequently with waveguide 143. In this fashion, the optical signal is routed from input port M to output port P. By properly arranging the relative placement of the movable waveguides 136, 138, the optical signal can be completely routed from input port M to any one of output

ports N-V, while limiting the motion of each of the movable platforms 136, 138 to only three positions (neutral, clockwise and counter-clockwise).

[0029] In the example embodiment illustrated in FIG. 2, each movable platform 136, 138 has a small number of positions (e.g., three positions), which allows each platform 136, 138 to move and locate in a "digital" manner: the movable platform 136, 138 has only two possible positions from its rest position. In this fashion, the movable platforms 136, 138 can be stopped using either mechanical hard stops or an electronic closed-loop control. The use of mechanical hard stops is preferred because it simplifies the design. As with the linear platform design, additional platforms or additional movable positions can be added to accommodate a larger number of output ports. The trade-offs for the rotational optical switch are similar to those for the linear optical switch.

[0030] In the example embodiment, the connection of an optical path over multiple waveguides requires the optical signal to "jump" across three air gaps 162, 164, 166. These air gaps should be kept small to minimize any optical losses. As explained above, the contributions to optical loss due to air gaps include the diffraction of light as it crosses free space and the reflection of light at interfaces. A virtue of MEMS technology is that the air gaps can be kept very small, thereby reducing the loss associated with the air gaps.

[0031] Referring to FIG. 2, the 1 x N optical switch has two movable platforms 136 and 138 supported by springs 144, 146, 148, which are in turn supported by support

structures 149, 162. The springs are designed to allow rotational movements, but resist radial movements. The movable platforms 136, 138 are suspended a distance over a cavity 160 that has been etched into the substrate 120. Methods of fabricating the optical switch structures as shown is discussed later.

[0032] Movable platforms 136, 138 can be rotated using actuators 150, 152, preferably formed out of the same structure as the platforms. These actuators are generally known in the MEMS industry as "comb" fingers and are known to those skilled in the art of MEMS design. In addition to actuation, comb structures can also be used for position sensing. The change in the capacitance as a result of the change in the relative position of the moving and stationary structures can be monitored to accurately determine the position of the moving structure. The stationary structures 154, 156 that supports the comb structures are suspended over the cavity 160 in the same way the moving platforms 136, 138 are suspended by their support structure 149. The actuators and sensors are connected by electrical traces routed to bonding pads 158.

<u>MEMS Process Description</u>

[0033] The following is the description of an example embodiment of an improved process for integrating optical waveguides and movable structures on silicon, where the details of the description are meant to be illustrative and not limiting. Referring to FIG. 3, the process starts with standard silicon on insulator (SOI) wafer 52 as the base substrate. Both silicon layers of the SOI assembly are specified to have the same properties: grade - prime; crystal orientation -100; dopant - P-type (Boron);

resistivity - 1-20 ohms/cm; surface quality - polished on both sides. Any standard wafer diameter can be used according to the number of devices the user requires or which can be efficiently laid out over the area. The thickness of the top SOI or device layer 53 is approximately 15 microns thick and lies over a 1 micron buried oxide layer 54. The base or handle wafer 55 can vary in thickness from 350- 750 microns depending upon the wafer diameter.

[0034] To produce the waveguides, a 5.7-micron layer of SiO_2 56 is deposited on each side of the wafer as shown in FIG. 4. A 1-micron layer of PECVD oxide 57 is then deposited. This is followed by deposition of another 3.7-micron layer of SiOxNy 58 as shown in FIG. 3. In the preferred embodiment of the improved MEMS process, a photolithography process etches back at least 2.4 microns of the SiOxNy to form the core of the waveguides 59. 4.6 microns of SiO2 is then deposited on the top surface as a cladding layer 60. A photoresist, mask and expose step is processed, etching the front and back surfaces to bare silicon, leaving the waveguide areas raised on top of the 15-micron SOI surface as shown in FIG. 7.

[0035] A photoresist, mask and expose step for bond pads and traces is then performed. A layer of metal is deposited and lifted off, leaving metalized traces 62. MEMS features are established by another photoresist mask and expose step, then etching, to remove 3-4 microns wide of silica in gap areas 63.

[0036] After the waveguides are processed, the underlying silicon structures (e.g., the combs, springs and platforms) need to be formed. In FIG. 8, an RIE (reactive ion

etch) process etches the gaps in the silica down through the 15-micron device layer to the SOI buried oxide 64. In FIG. 9, another lithography process on the wafer backside, followed by anisotropic wet etch through the wafer bottom to the SOI buried oxide layer 65, leaves 54.7-degree sidewalls. The silicon structure is finally "released" by etching the buried oxide layer, thus completely separates the gaps in the silicon 66.

[0037] Advantageously, the improved MEMS process allows one to etch from the bottom of the substrate and through the oxide. This is an advantage because the process provides a natural etch stop with the oxide and the final release is a DRY etch of oxides. Prior art processes of SOI rely on a wet etch of the oxide from the top (with etch holes on the structure). The process also provides electrical isolation for various electrodes by etching trenches on the device layer, forming electrical conductive traces separated by trenches on the sides, and by oxide on the bottom.

[0038] The improved process represents a simple and effective method of fabricating structures for the improved optical switch. Other processing techniques and materials (quartz, metal, alloys and ceramics) can be implemented to produce the same or similar configuration. The method and the sequence of fabrication can be altered to yield the same or similar finished device. For example, instead of using SOI, it is possible to bond two silicon wafers to produce the finished device. The phrase "semiconductor process" is intended to include bonding semiconductor wafers to produce a device. The advantage of bonding wafers is that the gap underneath the free structure can be produced without the need to create an opening from the bottom. Yet other contemplated processes involve dissolving the oxide underneath the structural layer by wet etching techniques.

To do so, the structural layer must have an opening to allow for the etchant to reach underneath the structural layer. These additional methods are generally well known to those skilled in the art of MEMS fabrication.

[0039] While various embodiments of the application have been described, it will be apparent to those of ordinary skill in the art that many more embodiments and implementations are possible that are within the scope of the subject invention. For example, each feature of one embodiment can be mixed and matched with other features shown in other embodiments. Features known to those of ordinary skill in the art of optics may similarly be incorporated as desired. Additionally and obviously, features may be added or subtracted as desired and thus, a movable platform having more than three or more positions is contemplated such that each position activates a different set of optical paths. As another example, the optical switch may accept more than 2 inputs and provide more than 2 outputs. The optical switch may be combined so as to create bigger optical switches with more ports. The 1 x N optical switch can be reversed to create a N x 1 optical switch, where an optical signal from one of N input ports is routed to the input port. Accordingly, the invention is not to be restricted except in light of the attached claims and their equivalents.